NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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A METHOD FOR THE DETERMINATION OF AIR INFILTRATION RATES IN AIRPLANE CABINS

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SUMMARY

A method for the experimental determination of the rate of infiltration of air into aircraft cabins during flight has been developed and tested. This method consists of releasing a quantity of gas in the cabin and calculating the infiltration rate from the measured rate of change of the gas concentration. The results of the flight tests indicate that after the infiltration rate is established at one altitude and airspeed, the infiltration rates at other altitudes and airspeeds can be calculated.

INTRODUCTION

The Ames Aeronautical Laboratory of the National Advisory Committee for Aeronautics has undertaken research for the purpose of evaluating factors which affect human comfort in airplane cabins. Available literature pertaining to the subject of heating, cooling, and ventilation of aircraft cabins has been reviewed to determine which factors require experimental investigation. The results of this review show that air infiltration is one of the principal factors causing a discrepancy between calculated and actual heating and cooling loads in unpressurized airplane cabins. It also has been observed that no method is currently employed for determining the air infiltration rates in aircraft cabins during flight. A method for the experimental determination of air infiltration rates has accordingly been proposed and has been investigated in the present research.

SYMBOLS

The following symbols are used throughout this report:

e	base of natural logarithms, 2.718 . . .
g	acceleration due to gravity, feet per second, second
I	infiltration rate, pounds per hour
I'	infiltration rate, cubic feet per minute
K	pressure-loss coefficient, dimensionless
M	molecular weight, pounds per mol
n	$(P_s - P_a)/q$, dimensionless
P	static pressure, pounds per square foot
ΔP	pressure differential, pounds per square foot
Q	flow rate, cubic feet per minute
q	free-stream dynamic pressure $\left(\frac{1}{2}\rho u^2\right)$ pounds per square foot
R	gas constant, feet per degree Fahrenheit
T	temperature of the air and gas mixture in the cabin, degrees Fahrenheit absolute
t	time, minutes
U	free-stream indicated velocity, miles per hour
u	free-stream true velocity, feet per second
V	volume of cabin, cubic feet
V_T	volume of sampling apparatus between cabin and sampling burette, cubic feet
W	weight, pounds
w	weight of gas per cubic foot of air entering the cabin, pounds per cubic foot

v specific volume of the gas at cabin temperature, cubic feet per pound

λ fraction by weight of the test gas in the cabin, dimensionless

λ_s fraction by weight of the test gas in the sampling burette, dimensionless

λ' fraction by volume of the test gas in the cabin, dimensionless

ρ mass density of air, slugs per cubic foot

Subscripts

a air in cabin

g gas in cabin

M mixture of air and gas leaving the cabin

m mixture of air and gas entering the sampling apparatus

o time equals zero

S standard sea-level conditions

s free stream

1 condition existing when the infiltration rate was measured

ANALYSIS

The method developed for determining the infiltration rate in an airplane cabin consists of releasing a quantity of gas in the cabin and calculating the infiltration rate from the measured rate of change of the gas concentration. The relation of the air infiltration rate to the measured rate of change of the concentration of gas in the cabin is determined as follows:

At time t if each cubic foot of air entering the cabin contains w pounds of gas and each cubic foot in the cabin contains W_g/V pounds of gas, the rate at which the gas is entering the cabin is wQ_M and the rate at which it is leaving the cabin is $W_g Q_M/V$. Thus, the rate of change of weight of gas in the cabin is

$$\frac{d(W_g)}{dt} = wQ_M - \frac{W_g Q_M}{V} \tag{1}$$

Separating variables and introducing limits yields, for equation (1),

$$\int_{W_{go}}^{W_g} \frac{d(W_g)}{(W_g - Vw)} = \int_{t_o}^{t} - \frac{Q_M}{V} \; dt \tag{2}$$

Integration of equation (2) gives

$$\log_e \frac{(W_g - Vw)}{(W_{go} - Vw)} = - \frac{Q_M t}{V} \tag{3}$$

It can be assumed that the air is infiltrating into the cabin at the same rate that the mixture is leaving, so that,

$$I' = Q_M$$

By this substitution, and also the substitution

$$W_g = \lambda W_M$$

where

$$W_M = \frac{P_M V}{R_M T}$$

and

$$R_M = \left[(1 - \lambda) R_a + \lambda R_g \right]$$

equation (3) becomes

$$\log_e\left(\lambda - \frac{R_M T w}{P_M}\right) = \log_e\left[\frac{(W_{go} - Vw)\, R_M T}{P_M V}\right] - \frac{I' t}{V} \qquad (4)$$

During any one test $\log_e\left[\frac{(W_{go} - Vw)\, R_M T}{P_M V}\right]$ is approximately constant for small gas percentages and constant operating conditions, and equation (4) can be assumed to be linear. The slope of the curve of $\log_e\left(\lambda - \frac{R_M T w}{P_M}\right)$ plotted as a function of t is then equal to I'/V. Thus, to obtain the infiltration rate I', the slope of the curve, $\log_e\left(\lambda - \frac{R_M T w}{P_M}\right)$ as a function of t, is multiplied by the cabin volume. The parameter $\left(\frac{R_M T w}{P_M}\right)$ represents the portion of the gas concentration in the cabin which was initially present before the test gas was released.

The concentration of the gas used in equation (4) is expressed as fraction by weight. In order to change fraction by volume, which is usually measured, to fraction by weight, the following relationship is employed;

$$\lambda = \frac{\lambda'_g M_g}{\lambda'_g M_g + \lambda'_a M_a} \qquad (5)$$

A graph of the concentration by weight in terms of the concentration by volume for carbon-dioxide gas, which was used in checking the method experimentally, is presented in figure 1.

When the airplane is on the ground and the infiltration rate is zero, the volume of the cabin can be determined with the same apparatus that is used to measure the infiltration rate. By releasing a known quantity of gas in the cabin and measuring the gas concentration which results, the cabin volume may be calculated from the following equation:

$$V = \frac{W_g v}{\lambda'} \tag{6}$$

Theoretically, the cabin volume can be determined also from the data by which the infiltration rate is calculated.

Extrapolation of the curve, $\log_e\left(\lambda - \frac{R_M T w}{P_M}\right)$ as a function of

t, to time equals zero, permits the determination of the gas concentration in the cabin just after the gas was released. Then the cabin volume can be calculated, knowing the gas concentration at time equals zero and the quantity of gas released. The high infiltration rates in cabins during flight, however, change conditions rapidly, and it is necessary to determine exactly when zero time occurs. In order to do this, it is necessary to know the time lag in the sampling method and the time required for releasing all the gas in the cabin. The difficulty encountered in establishing these time increments makes determination of the cabin volume by this method impractical, especially in view of the simpler method presented in the foregoing paragraph.

It is important that either the composition of the gas sample to be analyzed be the same as the composition of the gas in the cabin at the same instant of time or that the two compositions have a constant ratio throughout the test. The difference between the composition of the gas sample and the composition of the gas in the cabin at the same instant of time is a function of the volume of the sampling apparatus between the cabin and the point at which the gas sample is drawn into the sampling burette, the volumetric sampling rate, and the time interval between the initial release of the test gas and the time the sample is taken. The relationship between the true cabin concentration and the measured concentration may be expressed by

$$\frac{\lambda_2}{\lambda} = \left(1 - e^{-\frac{Q_m t}{V_T}}\right) \tag{7}$$

Equation (7) was derived in a manner similar to the derivation of equation (4).

When the infiltration rate is established at one altitude and airspeed, the infiltration rate for other conditions of altitude and airspeed may be calculated by the equation derived in the following paragraphs.

The static pressure in the airplane cabin will be equal to free-stream static pressure or will be equal to free-stream static pressure plus or minus a fraction of the free-stream dynamic pressure. The assumption is made, based on a limited amount of data, that this fraction is constant for various airspeeds and altitudes. The cabin pressure can then be expressed as

$$P_a = P_s \pm nq$$

where q is equal to $\frac{1}{2}\rho u^2$, the free-stream dynamic pressure. The pressure differential causing the air to infiltrate is then

$$\Delta P = (P_s + q) - (P_s \pm nq) = q(1 \mp n) = \frac{\rho}{2} u^2 (1 \mp n) \qquad (8)$$

The quantity of air flow through an opening in the fuselage can be expressed in terms of a pressure-loss coefficient and the square root of the air density and pressure differential across the opening. For two different conditions the equations are

$$I_1 = K\sqrt{\Delta P_1 \rho_1} \qquad (9)$$

and

$$I = K\sqrt{\Delta P \rho} \qquad (10)$$

Substituting equation (8) for the two conditions in equations (9) and (10), the relationship of the variables becomes

$$\frac{I_1}{I} = \frac{\rho_1}{\rho} \frac{u_1}{u} \qquad (11)$$

Indicated velocity is more generally used than true velocity; so the following substitutions are made in equation (11):

$$u_1 = \sqrt{\rho_S/\rho_1}\, U_1$$

and

$$u = \sqrt{\rho_S/\rho}\, U$$

Equation (11) then becomes

$$\frac{I_1}{I} = \sqrt{\rho_1/\rho}\, \frac{U_1}{U} \tag{12}$$

It can be seen from equation (12) that, for flight at the same altitude (i.e., ρ is equal to ρ_1), the equation for the infiltration rate at any airspeed, in terms of the airspeed at which the infiltration was measured, is

$$I = I_1 \frac{U}{U_1} \tag{13}$$

It follows that

$$I' = I'_1 \frac{U}{U_1} \tag{14}$$

For flight at constant indicated airspeed, the expression for the infiltration rate in pounds per hour at any altitude in terms of the altitude at which the infiltration was measured, from equation (12), is

$$I = I_1 \sqrt{\rho/\rho_1} \tag{15}$$

On substituting the expressions

$$I_1 = 60 \frac{\rho_1}{g} I'_1$$

and

$$I = 60 \frac{\rho}{g} I'$$

into equation (15), the expression for the infiltration rate in cubic feet per minute at any altitude in terms of the altitude at which the infiltration was measured is

$$I' = I'_1 \sqrt{\rho_1/\rho} \tag{16}$$

The values of $\sqrt{\rho/\rho_1}$ and $\sqrt{\rho_1/\rho}$ for NACA standard conditions have been plotted against altitude in figure 2 to be used as a multiplying factor (called infiltration factor). The value of ρ_1 has been taken as standard sea-level density. The infiltration rate at any altitude is then equal to the infiltration rate at sea level times the infiltration factor. If the infiltration rate in the cabin is measured at an altitude other than sea level, the infiltration rate should be divided by the infiltration factor to determine the infiltration at sea level. Infiltration rates at other altitudes then can be determined as previously described.

DESCRIPTION OF EQUIPMENT

The method for determining the infiltration rate in airplane cabins was tested in a Fairchild F-24-W40 airplane. A photograph of this airplane is shown in figure 3. The cabin is fabricated in a manner which prevents any appreciable air leakage through the walls, but openings around the door frames and windows are large and permit considerable leakage. Openings in the floor boards for rudder and stick controls also afford passages for infiltrating air.

In conducting the tests, carbon-dioxide gas was used because it was readily available and simple to analyze. An ordinary carbon-dioxide fire extinguisher with the nozzle removed was the source of the carbon-dioxide gas. In order to collect gas samples in the cabin, the following system was used. A venturi meter was located on the right-wing strut and the low-pressure tap connected to a small plenum chamber. The plenum chamber had 12 outlets. Six of the outlets were connected to evacuated sampling burettes and the other six were connected to rubber sampling tubes, the ends of which were located in various parts of the airplane. In flight, a portion of the cabin air was continually flowing from the cabin through the sampling tubes and plenum chamber to the low-pressure region at the venturi throat. A sample of cabin air could be taken at any time by opening a stopcock on one of the sampling burettes, thus allowing the sample to flow from the plenum chamber into the burette. The locations of the fire extinguisher and sampling burettes in the cabin are shown in figure 4. In figure 5 are shown the plenum chamber, the sampling burettes, and the sampling tubes which were distributed throughout the cabin. The tube at the bottom of the plenum chamber was connected to the low-pressure tap of the venturi meter, which is shown in figure 6. The concentration of carbon dioxide in the samples was determined with an Orsat gas analyzer.

During the short interval that the cabin was filled with carbon-dioxide gas the pilot and the observer breathed oxygen from portable oxygen bottles.

TESTS

The infiltration rate in the cabin of the airplane was measured in 2000-foot increments up to 10,000 feet pressure altitude, and at 70, 80, 100, and 120 miles per hour indicated airspeeds.

Prior to each flight the sampling burettes were evacuated and the fire extinguisher was filled with the quantity of carbon dioxide which would produce the desired concentration in the cabin. The concentration was limited in these tests by the range of the Orsat gas analyzer. When conditions of flight (i.e., airspeed and altitude) were set, the observer and the pilot applied their oxygen masks and the carbon-dioxide gas was released in the cabin. At 20-second intervals the observer opened the stopcock on one of the sampling burettes, allowed the gas in the plenum chamber to fill the burette, and then closed the stopcock. The samples were analyzed with the Orsat gas analyzer upon completion of the flight.

The experimental apparatus employed for measuring the infiltration rate and the experimental technique that was followed resulted from several preliminary flights.

A flight was made in which the gas samples were taken and analyzed directly with the gas analyzer during flight. It was found that the samples could not be analyzed in short enough intervals to measure the large infiltration rates. In the succeeding flights the evacuated sampling burettes were used.

Tests were conducted to determine if releasing the carbon-dioxide gas from one nozzle located in approximately the center of the cabin was sufficient to give proper distribution of the gas. The nozzle was on a short flexible hose and could be pointed in any direction. Expansion of the gas condensed the moisture in the air and a fog formed in the cabin. Observance of the fog formation indicated that the gas dispersed evenly throughout the cabin almost immediately. Analysis of the gas samples which were taken at different locations in the cabin showed that the variation in carbon-dioxide concentration was not greater than ±15 percent of the average concentration. In view of the good distribution indicated by the fog formation, it appeared that this difference in concentration was due mostly to infiltration drafts in the cabin rather than to insufficient distribution; so the single nozzle was used. In larger cabins a manifold system for distributing the gas will probably have to be employed.

The difference in the gas concentrations throughout the cabin, as indicated from the tests described in the foregoing paragraph, would not permit the over-all accuracy desired if a sample were taken at only one location in the cabin. In succeeding flights, to make certain that an average sample was obtained, samples were taken from six locations in the cabin simultaneously and collected in one sampling burette as described in a preceding section of this report.

Data obtained while using a hand aspirator as a suction source did not plot in a straight line. This indicated that the observer was unable to maintain a constant flow rate through the aspirator; so the venturi meter was employed to draw the gas samples from the cabin. The sampling rate was then dependent upon the speed of the airplane and remained constant during any run at constant airspeed. Use of the venturi meter also eliminated an operation by the observer.

The fire extinguisher which was used to release the carbon-dioxide gas originally had an expansion nozzle, but this was removed because the carbon dioxide solidified during the expansion process and filled the cabin with snow.

After the nozzle was removed, the only effect of the expansion cooling was the condensation of water vapor in the cabin. This condensed moisture evaporated rapidly,

RESULTS AND DISCUSSION

The tests conducted at various altitudes and airspeeds produced good results. The concentration of carbon dioxide in the cabin prior to the release of the test carbon dioxide was measured and found to be negligible. In figure 7 is shown a sample plot of $\log_e \lambda$ as a function of t. These data were taken at 6000 feet altitude and 70 miles per hour. The infiltration rate measured at various altitudes is plotted in figure 8. The solid line drawn on the graph is the theoretical trend curve calculated from equation (16) and drawn through one point at 2000 feet altitude. It can be seen that the measured values follow the theoretical curve; therefore, it is necessary to measure the infiltration rate at only one altitude. The infiltration rates at other altitudes can be calculated. The variation of the infiltration rate with indicated airspeed is shown in figure 9. The theoretical trend curve calculated from equation (14) is drawn through one experimental point at 70 miles per hour. The other points follow this curve; therefore, it is necessary to measure the infiltration rate at only one airspeed. Calculation of the infiltration rate for airspeeds at which the airplane is not in a normal flight position (e.g., at a high angle of attack with the flaps down) will probably result in an incorrect value because of the changed air flow around the fuselage.

Determination of the cabin volume from ground-test data and the use of equation (6) produced accurate results. There is a limitation, however, to the quantity of gas that can be released in the cabin. When too large a quantity of gas is released, the resulting high pressure will force a portion of the gas out through the openings in the cabin before the concentration can be measured. It has been found that errors due to this effect are negligible when quantities of carbon dioxide are used which will produce about 5-percent concentration in the cabin.

The ratio of the measured gas concentration to the true gas concentration in the cabin is given by equation (7). It will be noted that, for values of $-Q_m t/V_T$ greater than four, the ratio is very close to unity. For all data shown in this report, the calculated value of $-Q_m t/V_T$ was considerably greater than four, so that any error introduced by the difference in sampling rates at different airspeeds (due to the ram-actuated venturi) was negligible.

Data should not be taken while condensed moisture is in the air. Carbon dioxide which is absorbed in the water when the concentration is high will separate as time progresses and cause the concentration to be greater than it actually would be if there were no moisture present. This effect will decrease the slope of the $\log_e\left(\lambda - \frac{R_M T w}{P_M}\right)$ as a function of t curve, thus falsely indicating a low ventilation rate.

The discrepancy in the data taken under the same conditions of 70 miles per hour and 2000 feet altitude may be due to one of two reasons or a combination of both. The data were taken several days apart and a change in the airplane might have occurred during that time. The floor covering may have shifted or the air ventilators and the windows may not have been closed to the same degree of tightness. The discrepancy may be due also to error in measurement and analysis of the data. If it is assumed that all the discrepancy is due to this error, the maximum error is 8.5 percent. On the basis of these data, it can be concluded that the infiltration rate in airplane cabins during flight can be determined by this method with an over-all accuracy of at least ±10 percent.

CONCLUSIONS

A method for the experimental determination of air-infiltration rates in aircraft cabins during flight was developed and tested. The data from these tests indicated the following:

1. The infiltration rate in airplane cabins during flight can be determined by the method presented in this report.

2. When the infiltration rate has been established for one altitude and airspeed, the infiltration rate for any other conditions of altitude and airspeed can be calculated.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif., July 18, 1945.

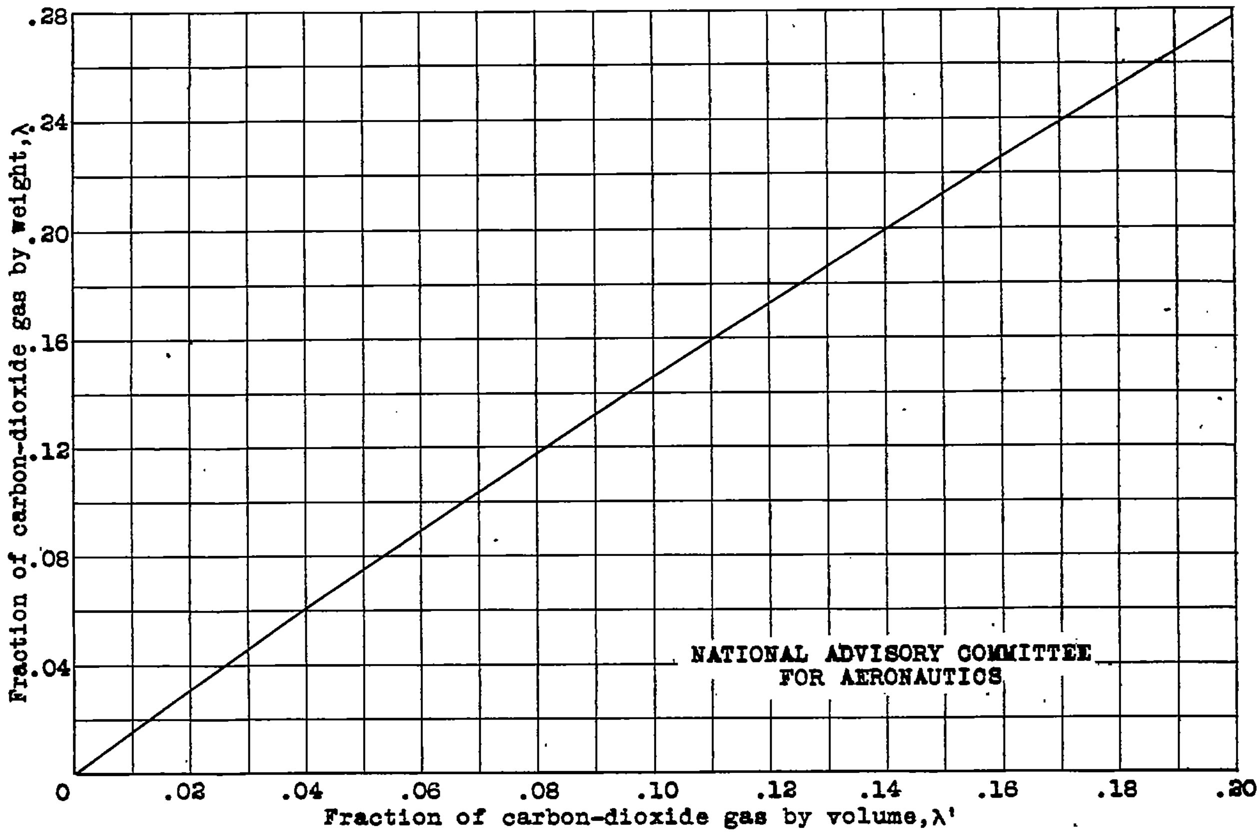

Figure 1.- Fraction of carbon-dioxide gas by weight in terms of the fraction by volume.

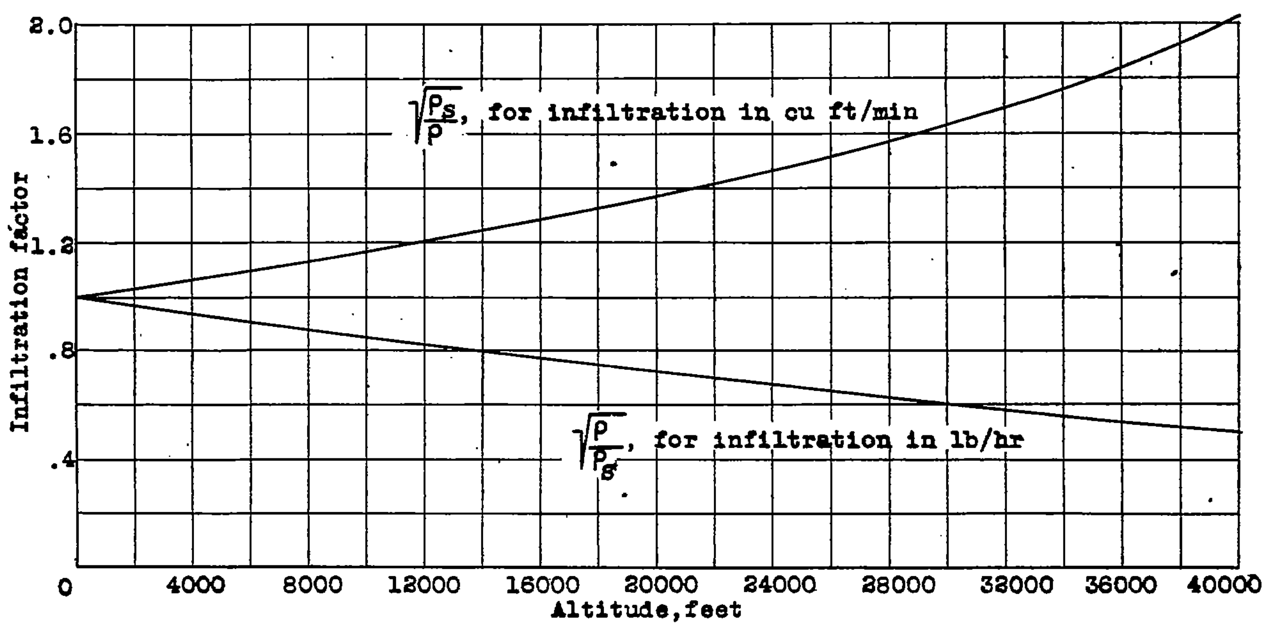

Figure 2.- Infiltration factor as a function of altitude, for determination of the infiltration rate at any altitude, in either cubic feet per minute or pounds per hour, from the infiltration rate at sea level.

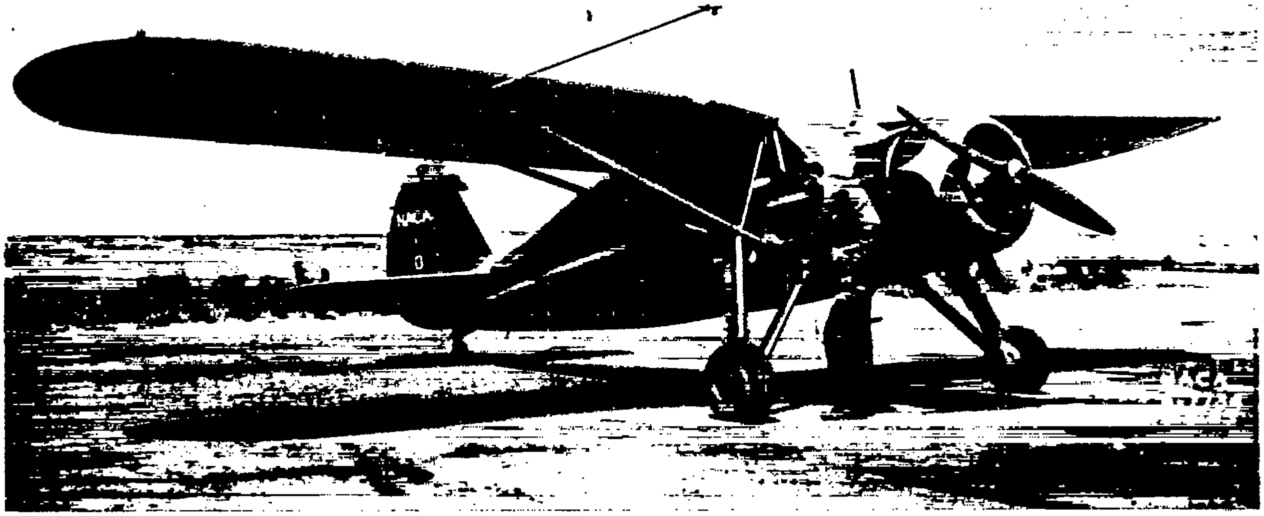

Figure 3.- Fairchild F-24-W40 airplane used for infiltration tests.

Figure 4.- Test airplane cabin showing the locations of the gas-sampling burettes and the fire extinguisher which was used to release the carbon-dioxide gas.

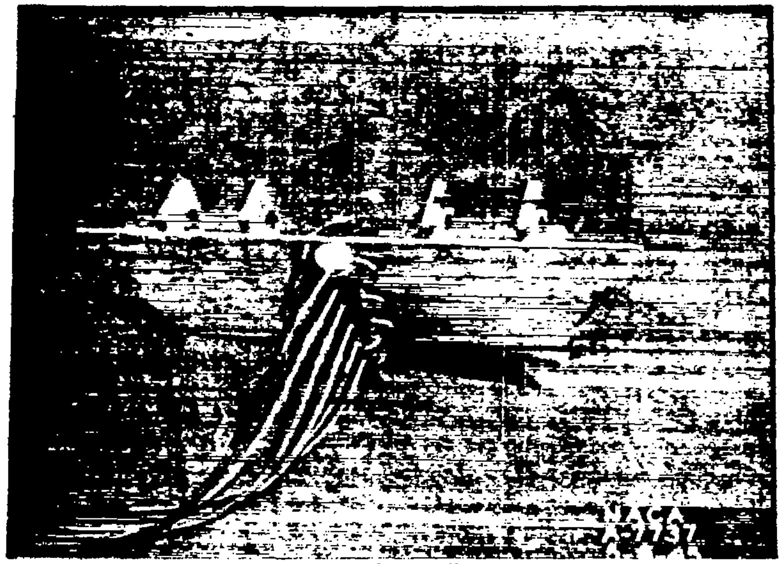

Figure 5.- Rack for sampling burettes showing plenum chamber with sampling tubes that were distributed throughout the cabin.

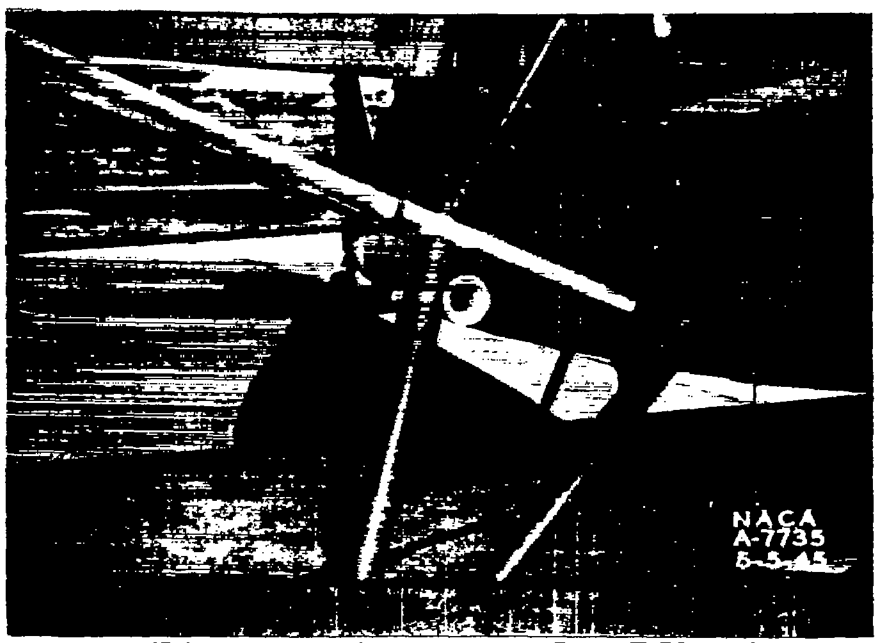

Figure 6.- Venturi meter attached to right landing strut.

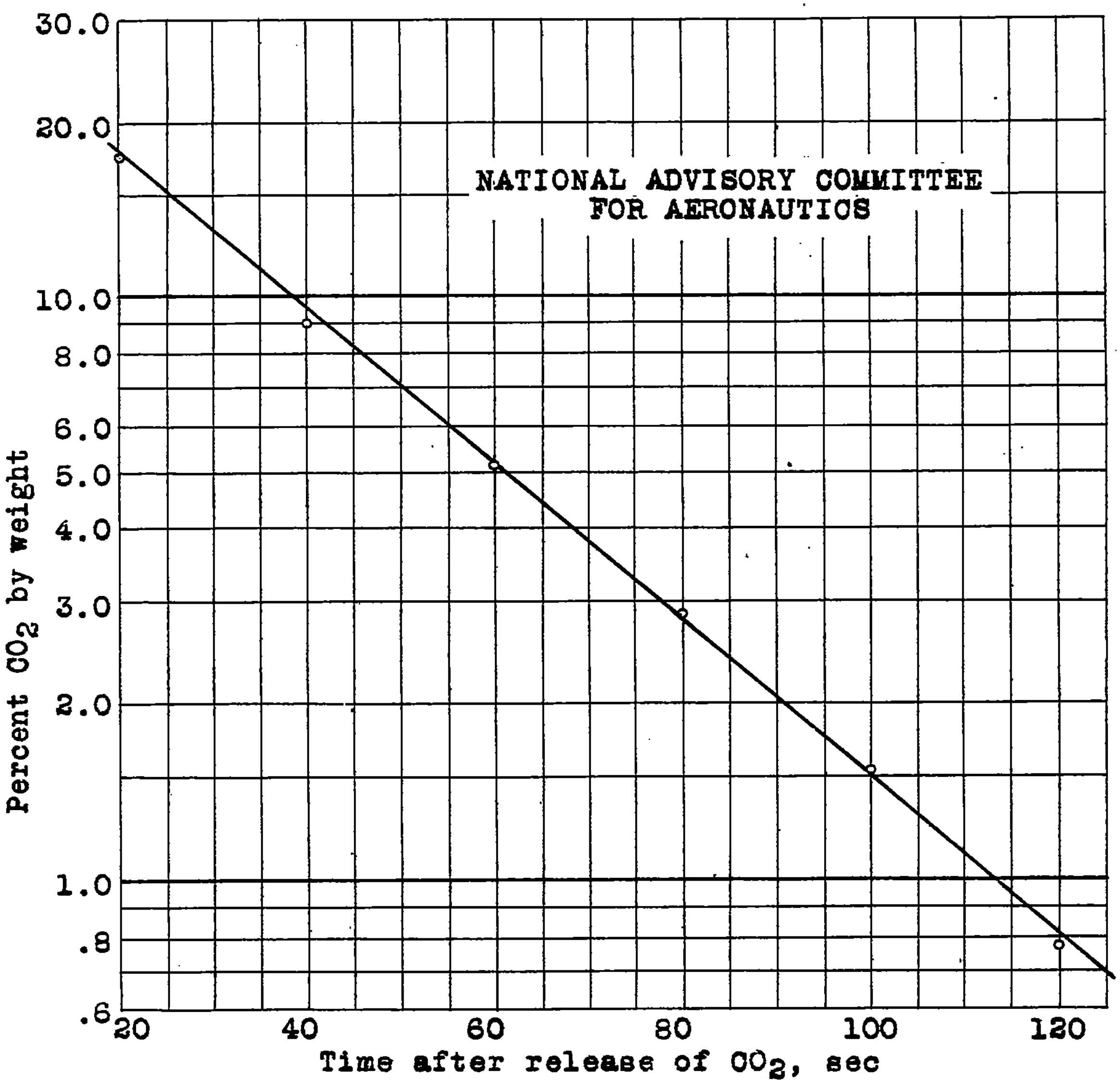

Figure 7.- Variation of the carbon-dioxide concentration by weight with time after a quantity of carbon-dioxide was released in the cabin. Pressure altitude, 6000 feet; indicated airspeed, 70 miles per hour.

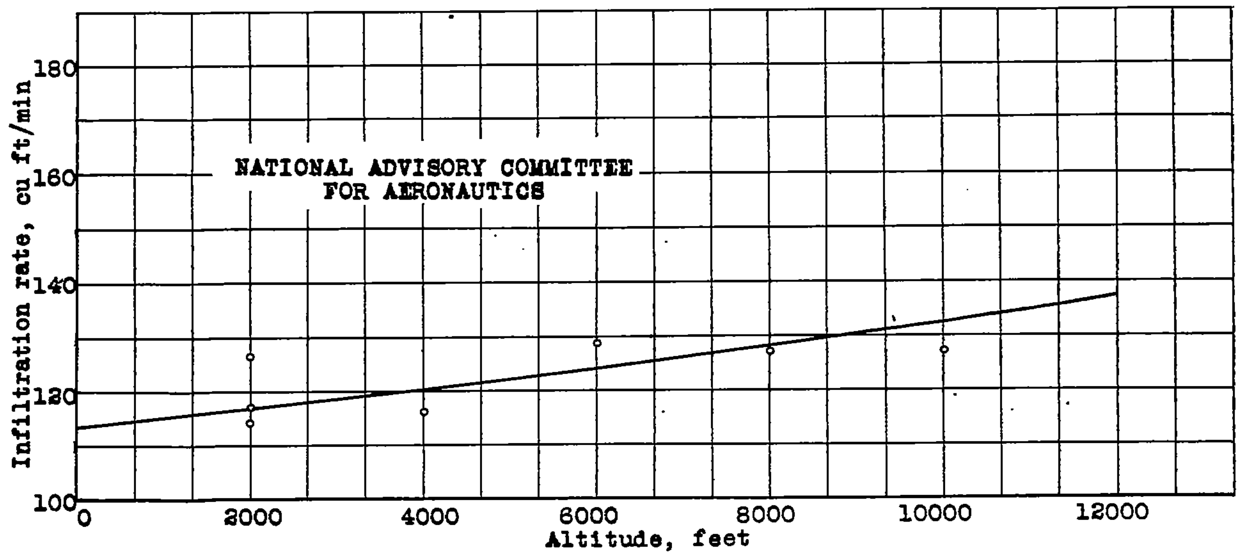

Figure 8.- Variation of the infiltration rate with altitude for a constant indicated airspeed. The line drawn on the graph is the theoretical trend curve calculated from equation (16) using one point at 2000 feet altitude as a basis.

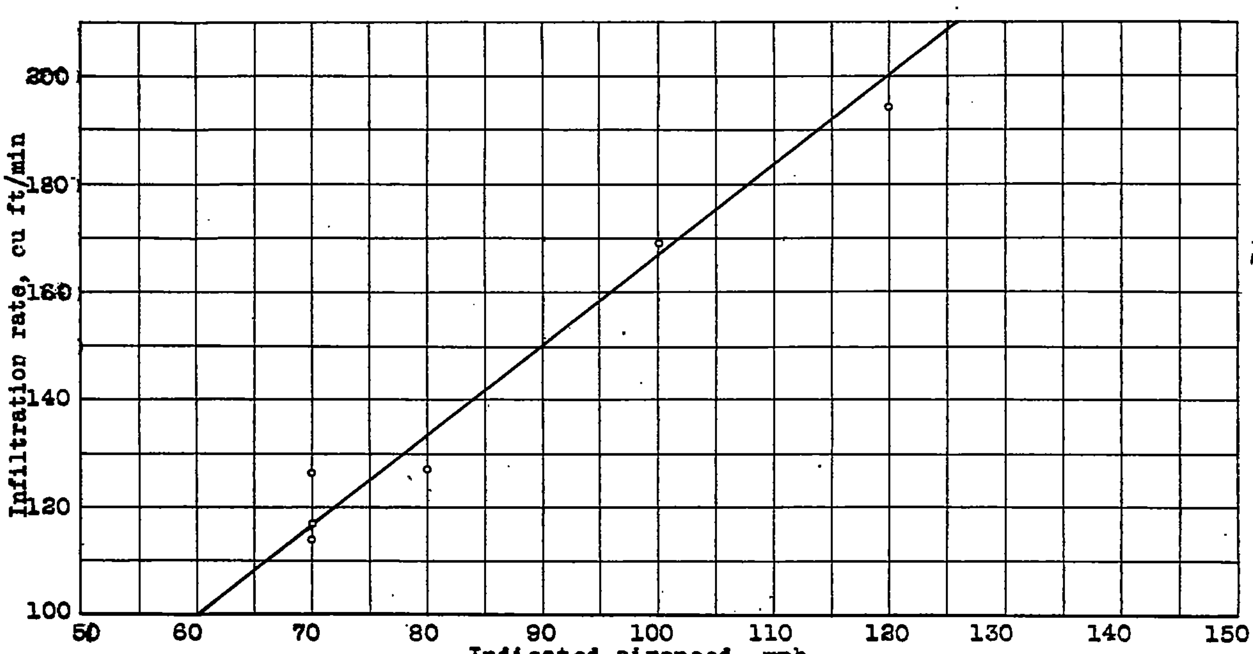

Figure 9.- Variation of the infiltration rate with indicated airspeed at 2000 feet altitude. The line drawn on the graph is the theoretical trend curve calculated from equation (14) using one point at 70 miles per hour as a basis.